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STRUCTURAL PERFORMANCE OF NEW THIN-WALLED CONCRETE SANDWICH PANEL SYSTEM REINFORCED WITH BFRP SHEAR CONNECTORS

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ABSTRACT

This paper presents a new thin-walled concrete sandwich panel system reinforced with basalt fiber-reinforced plastic (BFRP) with optimum structural performances and a high thermal resistance developed by Connovate and Technical University of Denmark. The shear connecting system made of a BFRP grid is described and provides information on the structural design with its advantages. Experimental and numerical investigations of the BFRP connecting systems were performed. The experimental program included testing of small scale specimens by applying shear (push-off) loading and semi-full scale specimens by flexural loading. Numerical investigations were based on 3-D linear elastic finite element analysis. Results from the numerical investigations were compared with experimental results of small and semi-scale specimens for the validation of the design procedure. Experimental and numerical results based on finite element modelling showed that the developed panel system meets the objectives of the research and is expected to have promising future.

KEYWORDS

BFRP, HPC sandwich panel, shear transfer, BFRP grid, precast concrete.

INTRODUCTION

According to EU (2010) residential and commercial buildings are responsible for about 40% of the total energy consumption and CO₂ emissions in Europe. Therefore, ambitious targets for energy consumption of new buildings are being implemented, and by the year 2020 nearly zero energy buildings will become a requirement in the European Union. As a consequence of these requirements as well as general requirements for increased efficiency and sustainability, the building sector experiencing a growing demand for modular, light and strong building elements having a high degree of insulation, a long life time, a low CO₂ emission, a low consumption of raw material, and an attractive surface with minimum maintenance. Thin-walled High Performance Concrete Sandwich Panels (HPCSPs) are an interesting option for future low or plus energy building constructions.

The HPCSPs have several beneficial features such as high quality, proven durability, fast erection, and attractive architectural appearance (Einea *et al.* 1994). A typical HPCSP consists of two precast High Performance Concrete (HPC) plates and layer of insulation separates the two HPC plates. The connectors penetrate the insulation layer and join the two HPC plates.

The HPCSPs may be designed with various degrees of composite action: non-composite, partially composite or fully composite (Rizkalla *et al.* 2009). The degree of composite action depends on the nature of the connection between two HPC plates. Two main categories of connectors exist: non-shear connectors and shear connectors. Non-shear connectors are used in non-composite HPCSPs primarily to resist the tensile forces required to maintain integrity of the panel by keeping two HPC plates attached. Shear connectors must provide adequate stiffness and strength to create significant composite behaviour in the panel and resist the ultimate and service loads on the panel. The connector design represents trade-off between establishment of full composite action for resisting lateral loads, and reduction of composite action to limit thermal deflections. The connections between the plates have been traditionally made by using bent reinforcing bars or various specially-designed steel or non-metallic connectors (Frankl *et al.* 2008). Increasing degree of composite action between two HPC plates using any type of these connectors increases the structural capacity of the HPCSP making it more efficient. However, increasing degree of composite action typically leads to significantly lower thermal efficiency of the panel due to the creation of thermal bridges (Wade *et al.* 1988). The stiffness of the connectors is proportional to the thermal deflection and thus has significant role in the design of HPCSPs.

Recently, the sandwich panel design concept has leaped forward by introducing fiber reinforced polymer (FRP) shear reinforcement due to the relatively high stiffness combined with its relatively low thermal conductivity compared to steel (Soriano and Rizkalla 2013). Wade *et al.* (1988) performed the first attempt to use Glass-fiber reinforced polymer (GFRP) connectors for insulated concrete sandwich walls. Salmon *et al.* (1997) introduced GFRP bars formed in a truss orientation in place of metal wire trusses. The experimental investigation showed that the use of GFRP resulted in a high level of composite action. Following the same concept, Morcous *et al.* (2010) and Maximos *et al.* (2007) studied different shapes of GFRC shear connectors to obtain the full composite action. In past few years Rizkalla *et al.* (2009) focused on use Carbon Fiber Reinforced Polymer (CFRP) shear connector grids. The use of CFRP grids as trusses has enabled significantly improve mechanical and thermal performances. Therefore, the insulation between to concrete plates can deliver 100 percent of its rated performance without the hot or cold spots typically found in connection with metal trusses.

This paper presents the research program performed to investigate the behaviour of thin-walled HPCSPs reinforced with basalt FRP (BFRP) shear connectors. There is a major potential for using BFRP grid or so called basalt geo-grid at a much lower cost, since the thermal conductivity and mechanical properties are similar to GFRP and the cost of BFRP is significantly cheaper than CFRP.

Previous generations of a HPCSP system studied at Department of Civil Engineering, Technical University of Denmark (DTU) showed a high level of thermal efficiency. However, these panels were not structurally efficient due to their non-composite behaviour (Figure 1a). Improvements were made to these panels to create partial composite action while maintaining sufficient thermal efficiency. Using a BFRP grid as shear reinforcement redefined limits of HPCSP performance. Non-corrosive BFRP grid is shaped to look like a truss, and then casted into the panel. The new insulation products enabled to use large solid blocks instead of several layers of insulation. This step significantly accelerates the production process, decreases the amount of waste product and especially provides direct transfer of shear stresses between two HPC plates (Figure 1b).

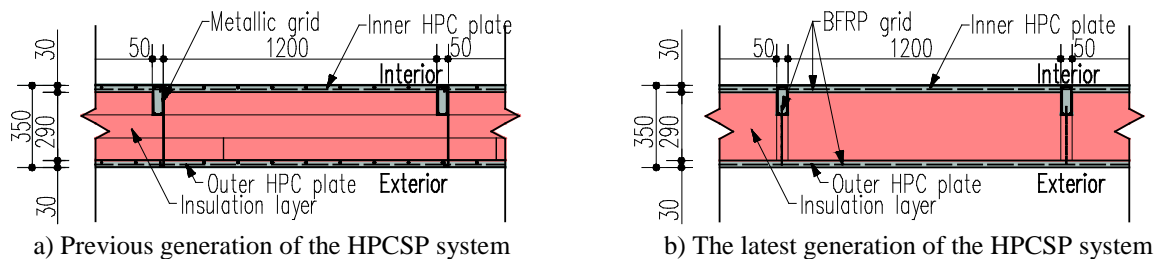


Figure 1. Evolution of the HPCSP system

EXPERIMENTAL PROGRAM

This paper describes an experimental research program performed at DTU to characterize the mechanical performance of the improved system. The program involved 25 small and semi-scale HPCSPs, which represent the panels that could be found installed on site. The first phase of experimental program consisted of material testing (insulation, HPC and BFRP grid) and pure shear (push off) test. The push-off testing was performed primarily to investigate shear transfer capacity of the insulation and BFRP grid. The push-off test has been used by a several researchers for similar purposes (Einea *et al.* 1994 and Salmon *et al.* 1997). The second phase of testing investigated flexural composite behaviour provided by the BFRP shear connectors. The specimen used to determine the level of composite action achieved by BFRP/insulation shear transfer mechanism are described in detail in the next section. Different parameters considered in the program included the type of BFRP grid used, insulation, rib structure, and the contact surface area of the insulation to HPC plate per strip of BFRP grid. Various parameters were established as part of experimental program that were believed to affect the overall structural performance and shear capacity of the BFRP shear connector transfer mechanism. All experimental investigations were also performed using Carbon FRP (CFRP) grid for direct comparison with BFRP grid.

TEST SETUP

Push-off Specimen Details

Twenty one specimens were produced; the size of each push-off specimen was 310 by 650mm with total thickness of 350mm. The specimen comprised two HPC plates and one layer of insulation (Sundolitt Expanded Polystyrene or Kingspan Free Rigid Phenolic insulation). The thickness of the insulation was 290mm. The top and bottom plate were casted using 110MPa HPC directly against insulation boards with thickness of 30mm. Shear connecting system was performed using BFRP or CFRP grid. The grid is made of 100% basalt or carbon continuous filament roving. The silane sizing was selected when making the fibers, which had component to

ensure elasticity of the yarn during textile process. The grid was sized 25 by 25mm with thickness of 0.9mm and coated with styrene-acrylic resin, and afterwards shaped to look like a truss. The push-off tests were performed by placing each specimen in a horizontal position and pushing the bottom plate relative to the top plate in a specially designed steel frame (Figure 2). The specimens were supported horizontally along the top plate, while the bottom plate was placed on low friction cylindrical roller bearings to move freely with the applied load. The load was applied by a 25kN hydraulic jack through a 30mm steel plate to provide a uniform distribution of the load to the HPC plate in three cycles; preloading in elastic range, unloading and loading until failure was reached under displacement control (speed rate 5mm/minute). The applied load was measured as well as the relative horizontal/vertical displacement between HPC plates at 7 locations. To compare the shear capacity, the different configurations (rib structure/connector type/insulation) were used, see Table 1.

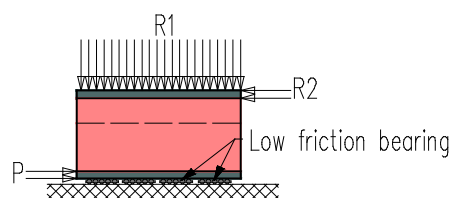


Figure 2. Test setup for push off specimens

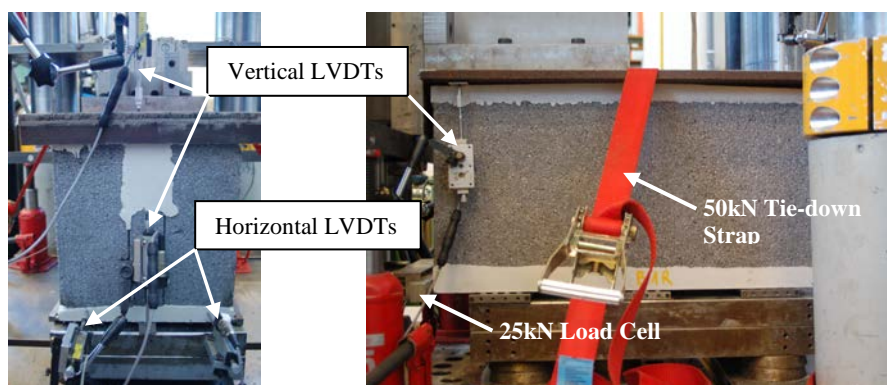
Flexural Specimen Details

The setup for all flexural specimens is shown in Figure 4a. 8 specimens were produced; the size of flexural specimen was 400 by 2000mm with a total thickness of 350mm. The panels were simply supported with a roller and pin configuration 110mm from the ends, creating a span length of 1780mm. The load was applied through a hydraulic actuator up to failure. The spreader beam made of two welded steel UPN profiles was used to distribute the load from the actuator to two 300mm long steel bars. The bars pressed directly on the interior HPC plate and produced two line loads. The applied load was measured as well as vertical deflection at four locations.

TEST INSTRUMENTATION

Push-off Test Instrumentation

Two types of instrumentation were used to monitor the behaviour of each specimen. A 25kN load cell measured the applied load, and 7 LVDT displacement transducers recorded the vertical and horizontal displacements of the HPC plates at various locations. The measurement was performed by placing the push-off specimen in a horizontal position to the specially designed steel frame. The HPC plate with smooth surface corresponding to the exterior side was put on low friction cylindrical roller bearings to minimize friction between HPC plate and bearings. The top steel plate was lowered to the specimen and tied with 50kN tie-down strap to eliminate vertical movements of the steel plate during testing. One LVDT was attached to the steel plate to monitor any unforeseen vertical movements. The measurement of horizontal displacements was determined by two LVDTs placed on the exterior HPC plate on one end and by one LVDT placed directly to the hydraulic jack. The vertical displacements were measured on the opposite side of each panel. Thin steel plates were fixed by two component epoxy glue at three locations to the specimens. Two LVDTs were attached on the left side to the thin steel plates connected to the interior HPC plate (Figure 3a). The last LVDT was placed on the thin steel plate as shown in Figure 3b.



a) Front view

b) Side view

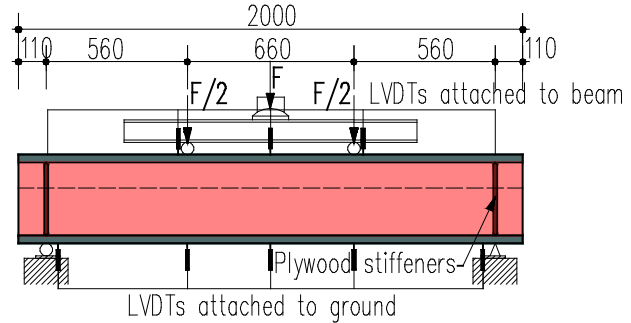
Figure 3. Instrumentation for push-off specimens

Flexural Test Instrumentation

A 100kN load cell recorded the applied load throughout the flexural testing of the HPCSPs. The specimens were positioned to the setup with interior HPC plate on top in order to avoid local cracking under load points. 8 LVDT displacement transducers measured vertical deformations. The exterior HPC plate was instrumented with LVDTs placed at mid span, each of the two load points and supports. The additional three LVDTs were attached to the interior HPC plate at mid span and each of the two load points as shown in Figure 4b.



a) Flexural test setup



b) Flexural test instrumentation

Figure 4. Test setup for flexural specimens

TEST RESULTS AND FAILURE MODES

Push-off Test Results and Failure Modes

The push-off test results indicate that all testing configurations had an effect on the shear strength of the proposed shear transfer mechanism. Nevertheless, the specimens did not exhibit pure shear failure due to the moment created by the eccentricity of the applied load and the two HPC plates. Therefore, results obtained from push-off testing can only be used for verification of the FE model and then correct boundary conditions applied to simulate the real panel behaviour under pure shear loading. The 3-D linear elastic FE model was performed using commercial software Abaqus. The HPC plate and insulation was modelled as eight-node solid elements whereas FRP was modelled as two-node beam elements. The results for 14 specimens (each configuration was duplicated) tested in push-off test are shown in Table 1.

Table 1. Push off test: Samples and results

| Insulation Type | Rib structure | Connector Type | Initial Shear Stiffness [kN/mm] |
|--|---------------|----------------|---------------------------------|
| Sundolitt Expanded Polystyrene (EPS) | No | No | 0.61 |
| | No | BFRP grid | 0.75 |
| | No | CFRP grid | 0.79 |
| | Yes | BFRP grid | 1.00 |
| | Yes | CFRP grid | 0.95 |
| CFC/HCFC Kingspan Free Rigid Phenolic insulation | No | No | 0.77 |
| | Yes | BFRP grid | 0.95 |

The HPCSPs made of CFC/HCFC Kingspan Free Rigid Phenolic insulation showed higher initial shear stiffness in comparison with those made with expanded polystyrene (EPS). Nevertheless, the panels with EPS reached higher ultimate shear strength. This difference in shear behaviour was caused by greater bond characteristic of EPS than CFC/HCFC Kingspan Free Rigid Phenolic insulation. The panels reinforced with BFRP grid reached similar initial shear stiffness as well as ultimate shear strength as the panels reinforced with CFRP grid. The configuration with CFC/HCFC Kingspan Free Rigid Phenolic insulation and BFRP led to a decrease of ultimate shear stiffness due to debonding between the insulation and HPC.

All push-off test specimens exhibited failure due to combination of debonding of insulation, rupture of tension cords in the BFRP and CFRP grid as well as buckling of the compression cords within the grid. In the case of CFC/HCFC Kingspan Free Rigid Phenolic insulation with BFRP and CFRP grid it was observed that grid was pulled out from HPC layer as depicted in Figure 5. All the specimens were shredded after testing; insulation layer was removed to the depth of BFRP and CFRP grid connectors. Furthermore, HPC faces were

examined; it was observed that the specimens with EPS insulation remained bonded, whereas the specimens with CFC/HCFC free rigid phenolic insulation showed clean HPC faces (Figure 6).

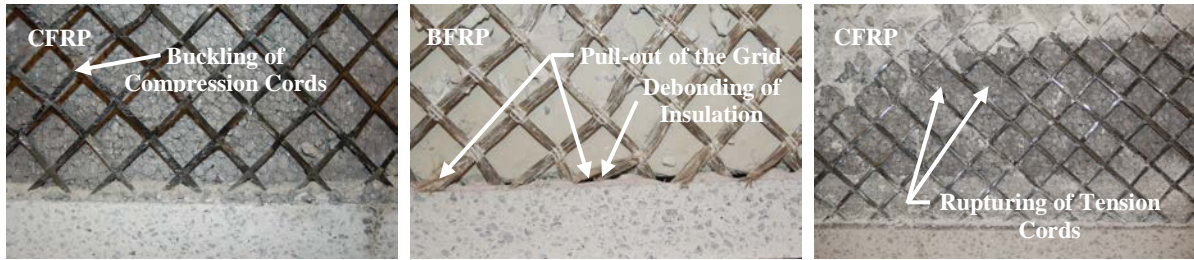


Figure 5. Typical failure modes of push-off test specimens

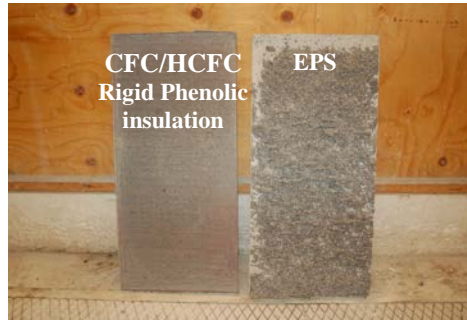


Figure 6. Typical HPC faces of push-off test specimens after failure

Flexural Test Results, Modelling and Failure Modes

The testing of the first flexural specimen indicated that the panel did not provide meaningful results to examine the level of composite action which can be achieved by using BFRP and CFRP grid. It was observed that the insulation layer was compressed from 290mm to almost 230mm at supports and load points. Therefore, it was decided to adjust the remaining panels by placing 15mm thick plywood to eliminate compression of insulation at supports. The load-deflection curve of the flexural specimens, compared to the theoretical one in case of full composite and non-composite action cross section is shown in Figure 7.

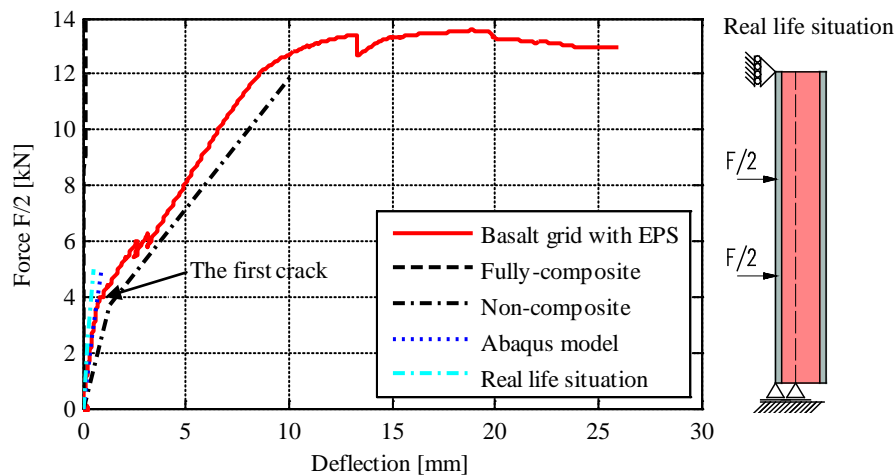


Figure 7. Typical load-deflection curve for flexural specimens

When comparing the panels subjected to four-point bending with EPS insulation and BFRP grid, and the specimens with CFRP grid, the results showed no obvious difference in overall capacity. In general, the specimens with EPS insulation provided higher overall bending capacity in comparison with the CFC/HCFC Kingspan Free Rigid Phenolic insulation.

The observed flexural behaviour in comparison with the theoretical full composite and non-composite action indicated that the specimens behave only with partial composite action, i.e. 53% composite action. The partial composite behaviour is caused by compression of insulation. Furthermore, buckling of FRP grid was observed within insulation layer which prevented the panel from obtaining the expected composite action. Moreover, the

shear slip between insulation layer and HPC plates was observed as a typical fracture mode, often experienced with a partial composite action. The obtained composite level is not representative of the expected composite behaviour. The used boundary conditions were different than in the HPCSPs mounted at the building site. In general, only the interior plate is constrained and the exterior is free to move. Therefore, the results obtained from flexural testing can only be used for verification of the FE model and then correct boundary conditions applied to simulate the real panel behaviour.

CONCLUSIONS

Push-off Test

The HPCSPs made of CFC/HCFC Kingspan Free Rigid Phenolic insulation showed higher initial shear stiffness in comparison with those made with expanded polystyrene (EPS). Nevertheless, the panels with EPS reached higher ultimate shear strength likely due to higher bond capacity. The panels reinforced with BFRP grid reached similar initial shear stiffness as well ultimate shear strength as the panels reinforced with CFRP grid.

Flexural Test

The results of the panels subjected to four-point bending showed no obvious difference in the overall capacity between the specimens with EPS insulation and BFRP grid, and the specimens with CFRP grid. In general, the specimens with EPS insulation provided a higher overall bending capacity in comparison with the CFC/HCFC Kingspan Free Rigid Phenolic insulation. The observed flexural behaviour in comparison with the theoretical composite and non-composite action indicated that the specimens behave only with partial composite action i.e. 53% composite action. The partial composite behaviour is caused by a combination of buckling of FRP grid, compression of insulation and shear slip between insulation layer and HPC plates.

Numerical modelling

Numerical investigations were based on 3-D linear elastic finite element analysis using commercial software Abaqus. Results from the numerical investigations were compared with experimental results of small and semi-scale specimens for the validation of the design procedure. A good correlation was observed between the results in the linear elastic range.

Experimental and numerical results based on finite element modelling showed that the developed panel system meets the objectives of the research and is expected to have promising future.

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